

# Decay studies of $^{288-287}_{115}$ alpha-decay chains

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## Abstract

The  $\alpha$ -decay chains of  $^{288-287}_{115}$  are studied along with the possible cluster decay modes by using the preformed cluster model (PCM). The calculated  $\alpha$ -decay half-lives are compared with experimental data and other model calculations. The calculated Q-values, penetration probabilities and preformation probabilities factors for  $\alpha$ -decay suggest that  $^{283}_{170}113$ ,  $^{287}_{172}115$  and  $^{272}_{165}107$  parent nuclei are more stable against the  $\alpha$ -decay. These alpha decay chains are further explored for the possibilities of cluster decay. Decay half lives of different cluster from different nuclei of the decay chains point to the extra stability near or at the deformed shells  $Z = 108$ ,  $N = 162$  and  $Z = 100$ ,  $N = 152$ . The decay half-lives for  $^{14}C$  and  $^{48}Ca$  clusters are lower than the current experimental limit ( $\approx 10^{28}$ sec).

**Key Words:** Alpha decay, cluster radioactivity, Super-heavy Elements, Half-life

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# 1 Introduction

The synthesis of superheavy elements and their decay studies is a long term goal of nuclear structure physics. These days advancement in the radioactive nuclear beam facilities has opened the door to reach the center of island of superheavy elements. Understanding nuclear stability/instability in the superheavy mass region is also a long standing question. Firstly in 1969 Flerov [1] suggested the use of a highly neutron-rich beam of  $^{48}\text{Ca}$  for the formation of superheavy elements with neutron rich targets such as  $^{244}\text{Pu}$ ,  $^{248}\text{Cm}$  and  $^{252}\text{Cf}$ .

Many superheavy elements have been synthesised at GSI, Dubna, RIKEN and LBNL. The progress of the synthesis of odd  $Z$  nuclei is rather slow as compared to even  $Z$  nuclei. The nuclei in superheavy mass region are investigated through the measurement of energies of alpha particles belonging to the characteristic chains of such superheavy elements. The most important decay parameters for these decay chains are Q-value of the decay and the half-life time. Extensive attempts have been made to calculate the alpha decay half lives theoretically. Alpha decay half-life are very sensitive to the Q-values and the Q-values depend on the mass of parent and daughter nuclei. Different approaches have been adopted to find the nuclear mass in the superheavy region. In recent years, a number of papers in which alpha decay has been studied by determining the Q-value from different mass tables and then putting it into different formalisms to calculate alpha decay half lives have appeared [2, 3, 4, 5, 6]. In [7, 8] Attempts to find the properties of the nuclei that belong to the alpha decay chain of the superheavy elements have also been made.

Recently two alpha decay chains  $^{288}115$  and  $^{287}115$  have been observed [9] in the 3n- and 4n- evaporation channels with cross sections of about 3pb and 1pb respectively, using the  $^{48}\text{Ca}$  beam with  $^{243}\text{Am}$  target. These two decay chains have been studied [10, 11, 12, 13, 14, 15] for the ground state properties using various theoretical models. The purpose of this work is to study the alpha decay and cluster decay half-lives of superheavy nuclei and the shell closure effects if any, within the Preformed Cluster Model (PCM). In the first part of the calculations alpha decay half-lives are calculated for both the alpha decay chains. Second part of the calculation covers compar-

ative study of alpha decay half-lives for both  $^{288-287}_{115}$  decay chains with other theoretical model calculations and also calculation within the framework of PCM model by taking different Q-values from experimental data i.e. PCM model calculation, Myers-Swiatecki and from Muntian nuclear data table. These calculated half-lives have been compared with the experimental results. Heavy nuclei of trans lead region are well known alpha emitters and these nuclei also undergo exotic cluster decay that was predicted by Poenaru et.al. in 1980 [16]. After the first experimental observation of cluster decay by Rose and Jones [17], different approaches have been followed to understand cluster decay [18, 19] and it is very well established mode of decay. Finally the theoretical calculations for the emission of such exotic cluster heavier than alpha particle from the nuclei belonging to the alpha decay chain of superheavy elements have been made.

The Preformed Cluster Model (PCM) is described briefly in Section 2 and the results of calculation are presented in Section 3. Discussion and summary of results is given in Section 4.

## 2 The preformed cluster model

The Preformed Cluster Model (PCM) [20, 21, 22] uses the dynamical collective coordinates of mass and charge asymmetries

$$\eta = (A_1 - A_2)/(A_1 + A_2)$$

and

$$\eta_Z = (Z_1 - Z_2)/(Z_1 + Z_2),$$

first introduced in the Quantum Mechanical Fragmentation Theory [23, 24, 25, 26, 27, 28]. These are in addition to the usual coordinates of relative separation  $R$  and deformations  $\beta_i$  ( $i = 1, 2$ ). Then, in the standard approximation of decoupled  $R$ - and  $\eta$ -motions [20, 21, 29], The decay constant  $\lambda$  (the decay half-life  $T_{1/2}$ ) in PCM is defined as

$$\lambda = \frac{\ln 2}{T_{1/2}} = P_0 \nu_0 P. \quad (1)$$

Here  $P_0$  is the cluster (and daughter) preformation probability and  $P$  the barrier penetrability which refer, respectively, to the  $\eta$  and  $R$  motions. The  $\nu_0$  is the barrier assault frequency. The  $P_0$  are the solutions of the stationary Schrödinger equation in  $\eta$ ,

$$\left\{ -\frac{\hbar^2}{2\sqrt{B_{\eta\eta}}} \frac{\partial}{\partial \eta} \frac{1}{\sqrt{B_{\eta\eta}}} \frac{\partial}{\partial \eta} + V_R(\eta) \right\} \psi^{(\nu)}(\eta) = E^{(\nu)} \psi^{(\nu)}(\eta), \quad (2)$$

which on proper normalization are given as

$$P_0 = \sqrt{B_{\eta\eta}} \left| \psi^{(0)}(\eta(A_i)) \right|^2 (2/A), \quad (3)$$

with  $i=1$  or  $2$  and  $\nu=0,1,2,3,\dots$ . Eq. (2) is solved at a fixed  $R = R_a = C_t (= C_1 + C_2)$ . The  $C_i$  are Süssmann central radii  $C_i = R_i - (1/R_i)$ , with the radii  $R_i = 1.28A_i^{1/3} - 0.76 + 0.8A_i^{-1/3} fm$ .

The fragmentation potential  $V_R(\eta)$  in (2) is calculated simply as the sum of the Coulomb interaction, the nuclear proximity potential [30] and the ground state binding energies of two nuclei,

$$V(R_a, \eta) = -\sum_{i=1}^2 B(A_i, Z_i) + \frac{Z_1 Z_2 e^2}{R_a} + V_P, \quad (4)$$

with  $B$ 's taken from the 2003 experimental compilation of Audi et al. [31] and from the 1995 calculations of Möller et al. [32] whenever not available in [31]. Thus, full shell effects are contained in our calculations that come from the experimental and/or calculated [32] binding energies.

The charges  $Z_1$  and  $Z_2$  in (4) are fixed by minimizing the potential in  $\eta_Z$  coordinate. The Coulomb and proximity potentials in (4) are for spherical nuclei. The mass parameters  $B_{\eta\eta}(\eta)$ , representing the kinetic energy part in (2), are the classical hydrodynamical masses [33].

The WKB tunnelling probability, calculated is  $P = P_i P_b$  with

$$P_i = \exp\left[-\frac{2}{\hbar} \int_{R_a}^{R_i} \{2\mu[V(R) - V(R_i)]\}^{1/2} dR\right] \quad (5)$$

$$P_b = \exp\left[-\frac{2}{\hbar} \int_{R_i}^{R_b} \{2\mu[V(R) - Q]\}^{1/2} dR\right]. \quad (6)$$

These integrals are solved analytically [21] for  $R_b$ , the second turning point, defined by  $V(R_b) = Q$ -value for the ground-state decay. The assault frequency  $\nu_0$  in (1) is given simply as

$$\nu_0 = (2E_2/\mu)^{1/2}/R_0, \quad (7)$$

with  $E_2 = (A_1/A)Q$ , the kinetic energy of the lighter fragment, for the  $Q$ -value shared between the two products as inverse of their masses.

### 3 Calculations and Results

In Fig.1 decay characteristics of both alpha decay chains  $^{288}_{115}$  and  $^{287}_{115}$  are shown. The maximum half-life for the alpha decay chain of  $^{287}_{115}$  is found at  $^{283}_{170}\text{113}$ ,  $^{287}_{172}\text{115}$  parent nuclei indicating that these are more stable against the alpha decay. This stability can be attributed to either the magicity of protons at  $Z = 114$  or of neutrons at  $N = 172$  or to both. The alpha decay half-life for  $Z = 107$ ,  $N = 165$  is very high in alpha decay chain of  $^{288}_{115}$ . Smaller  $Q$ -value should mean a relative decrease in the penetrability  $P$ , shown in Fig. 1. The preformation factor  $P_0$  is smaller for  $^{283}_{170}\text{113}$ ,  $^{287}_{172}\text{115}$  and  $^{272}_{165}\text{107}$  parent nuclei and in present calculations it is smaller as compared to those for the actinides [34]. There is discontinuity for the half-lives between  $^{279}_{111}$  and  $^{283}_{113}$ . Such discrepancies in the decay of superheavy nuclei have been reported earlier also [35]. One of the reasons may be the assumption that we are considering alpha decay from the ground state of the parent to the ground state of daughter, whereas the possibility of alpha decay from excited state also exists [36] in addition to this there is very large uncertainty in the experimental data for these two nuclei. Further experimental data would be useful in understanding this behaviour. In Fig. 2 the  $PCM$  based calculations for  $^{288}_{115}$  and  $^{287}_{115}$  alpha decay half-lives are compared with the experimental data. The calculations based on other theoretical models are shown in the figure and these are also given in Table 1. The calculated results in  $PCM$  in general follow the trend of experimental data as is evident from the figure. We took  $Q$ -values from experimental data ( $Q_{exp}$ ) [9] and from different models i.e. Myers-Swiatecki ( $Q_{MS}$ ) as well as Muntian et al. nuclear data table ( $Q_{MU}$ ) from Ref.[3], whereas  $PCM$  ( $Q_{PCM}$ ) has been calculated using Audi et al.[31]

and Moller et al. nuclear data table[32]. Using these Q-values we calculated  $\alpha$ -decay half-lives for  $^{288}115$  decay chain within the framework of PCM model. The results of these calculations are shown in Fig.3. These calculated half-lives are compared with the experimental results. In this analysis it is found that calculated  $\alpha$ -decay half-lives using Muntian's  $Q_{MU}$ -value in PCM improves the agreement with the experimental results for this decay chain. Similar comparison for  $^{287}115$ -decay chain is presented in Fig.4.

The second part of the calculations is done to look for any possibility of cluster decays from these two  $^{288-287}115$  alpha decay chains. In Fig. 5, the calculated cluster decay half-lives of various possible clusters are shown with the Q-values for  $^{288}115$ . The choice of the clusters is based on the minima in the fragmentation potentials  $V(\eta)$ [37]. The Q-value increases as the size of the cluster increases, its increase with the mass of parent nucleus is smooth and linear. The study of half lives of different cluster decay modes tells about the shell effects. Higher value of half life indicate the presence of shell stabilised parent nucleus, whereas comparatively low value of half life tells the same about the daughter and cluster nuclei. A careful analysis of different cluster emissions from the nuclei of alpha decay chain of  $^{288}115$  shows that the shell stabilising effect is seen in the decay of  $^{10}Be$  from  $^{272}107$  nucleus since decay half life for this cluster peaks at this parent nucleus. Also in  $^{10}Be$ ,  $^{14}C$ , and  $^{26}Ne$  decay of  $^{280}111$  nucleus a minimum is seen therefore these decays lead to deformed daughters with (Z, N) values as (107, 163), (105, 161) and (101, 153) respectively. It points to extra stability near the deformed shells ( $Z = 108$ ,  $N = 162$ ) and ( $Z = 100$ ,  $N = 152$ ) as investigated in [38, 39]. The cluster preformation ( $P_0$ ) and penetration (P) probabilities are shown in Fig. 6. Since assault frequency ( $\nu_0$ ) remains almost constant, the decay half-life is a combined effect of preformation ( $P_0$ ) and penetration (P) probabilities. From Fig. 6 it is clear that  $^{10}Be$  has higher  $P_0$  as compared to clusters  $^{14}C$ ,  $^{20}O$ ,  $^{23}F$ ,  $^{26}Ne$ ,  $^{28}Mg$ ,  $^{34}Si$  and  $^{48}Ca$  but its penetration probability is smaller as compared to different clusters yet it has larger half-life than the others. Similar calculations made for the second alpha decay chain  $^{287}115$  are shown in Fig. 7 and Fig. 8. In Fig. 7, similar to Fig. 5 prominent shell effects are seen in some of the cluster decay modes. High value of half life for the decay of  $^{10}Be$  from  $^{271}107$  nucleus may be due to deformed magicity of  $Z = 107$  and  $N = 164$ . Also the presence of minimum in the half life of

$^{14}\text{C}$ , and  $^{24}\text{Ne}$  decay from  $^{279}111$  nucleus points to the extra stability of the daughter with  $Z = 105$ ,  $N = 160$  and  $Z = 101$ ,  $N = 152$ . Interestingly it is found that decay half-life of  $^{48}\text{Ca}$  cluster from all parent nuclei of this decay chain lies within the experimental limits  $\sim 10^{28}\text{s}$ [40].

## 4 Summary

In this paper PCM based calculation have been used study alpha and cluster decay of two decay chains of  $^{287}115$  and  $^{288}115$  nuclei. A comparative study of both the  $\alpha$ -decay chains has been carried first. Alpha decay half-lives are compared with the experimental data and the other available theoretical calculations. The PCM calculation results in general follow the experimental data.

Not only PCM calculation results are compared with the experimental data and other theoretical models but also the role of Q-value in half-life is studied. Then we calculated the half-life using PCM model by taking the Q-values from experimental data ( $Q_{exp}$ ), PCM model( $Q_{PCM}$ ), Myers-Swiatecki ( $Q_{MS}$ ) and from Muntian ( $Q_{MU}$ ) nuclear data table. It is found that the use of ( $Q_{MU}$ ) provides better agreement with the experimental results. Also, a small change in Q-value produce a large variation in half-life, which indicates the sensitivity of half-lives towards the Q-values.

Finally, cluster decay calculations made for both  $\alpha$ -decay chains  $^{288-287}115$  with a view to see if there is any branching of the  $\alpha$ -decay to another light nucleus due to the spherical and/or deformed magicity of the corresponding heavy daughter nucleus. After a careful analysis of the two alpha decay chains  $^{288-287}115$ , which offers some possibilities of cluster emission such as  $^{10}\text{Be}$ ,  $^{14}\text{C}$ ,  $^{26}\text{Ne}$  from  $^{279-280}111$ . The decay half-lives of  $^{14}\text{C}$  cluster decay from  $^{284}113$  and  $^{280}111$ ,  $^{48}\text{Ca}$  from  $^{288}115$  and  $^{284}113$  lies within the range of experimental limits.

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## Figure Captions

Fig. 1 The  $\alpha$ -decay half-lives, Q-values, preformation and the penetration probabilities calculated on the basis of PCM plotted as a function of the parent nucleus charge for the  $\alpha$ -decay chains of  $^{288-287}\text{115}$ .

Fig. 2 The  $\alpha$ -decay half-lives calculated on the basis of PCM and comparison with experimental data[9] and those calculated on the basis of the Delta2[11], NL3 parameter calculation[12], DDM3Y effective interaction[13], GLDM and VSS from[15] plotted as a function of the parent nucleus mass for the  $\alpha$ -decay chains of  $^{288-287}\text{115}$ .

Fig. 3 The  $\alpha$ -decay half-lives and the Q-values are plotted as a function of the parent nucleus mass for the  $\alpha$ -decay chain of  $^{288}\text{115}$ . The  $\alpha$ -decay half-lives are calculated using experimental Q-values ( $Q_{exp}$ )[9] and theoretical Q-values from the PCM model calculation( $Q_{PCM}$ ), Myers-Swiatecki( $Q_{MS}$ ) and from Muntian et al. nuclear data table( $Q_{MU}$ ). The ( $Q_{MS}, Q_{MU}$ ) values are taken from Ref.[?] while( $Q_{PCM}$ ) is calculated using the Audi-Wapstra mass table[31] and Möller et al. nuclear data table[32].

Fig. 4 The same as for Fig. 3 but for the  $^{287}\text{115}$   $\alpha$ -decay chain.

Fig. 5 The calculated half-lives and the Q-values for different cluster decays on the basis of PCM model plotted for the parent nuclei belonging to  $\alpha$ -decay chain of  $^{288}\text{115}$ .

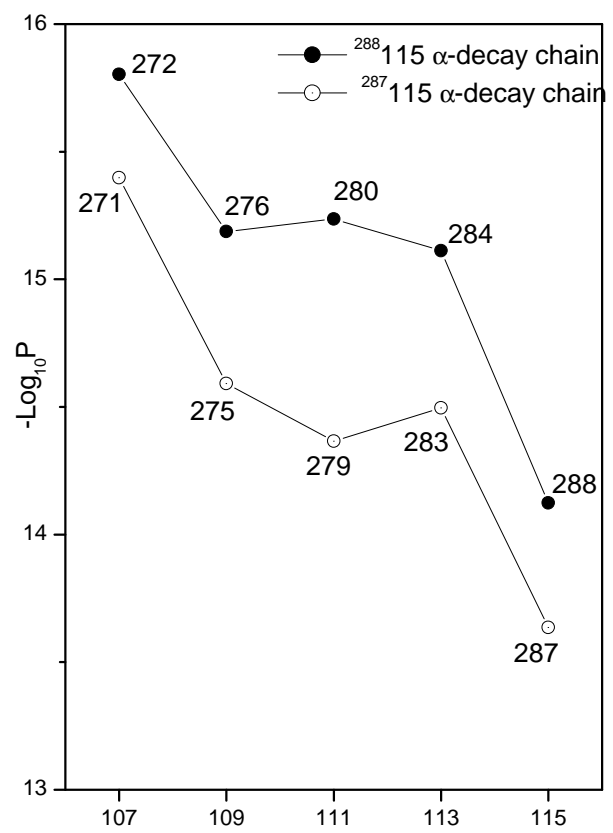
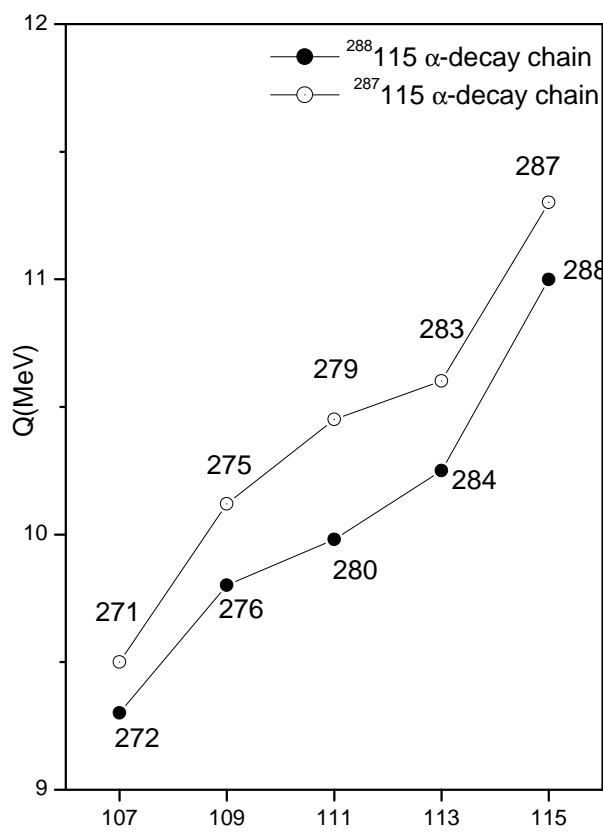
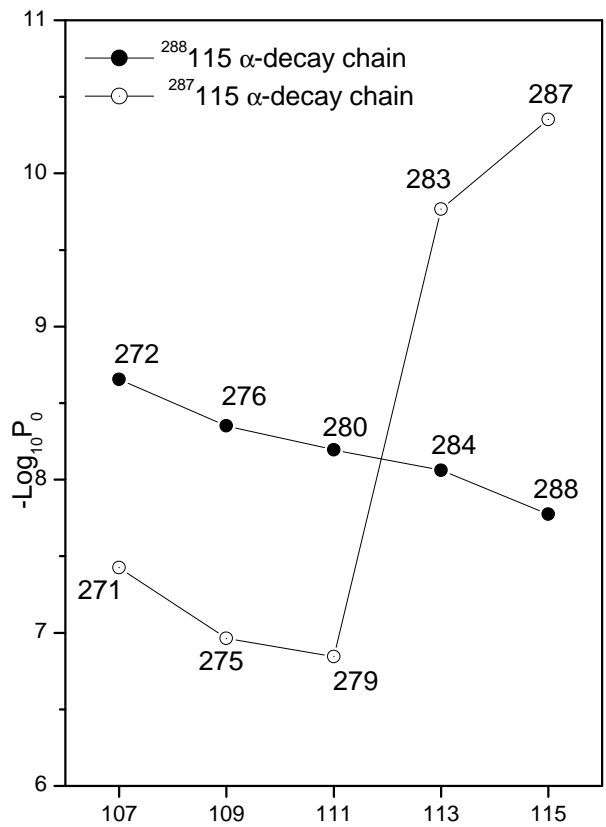
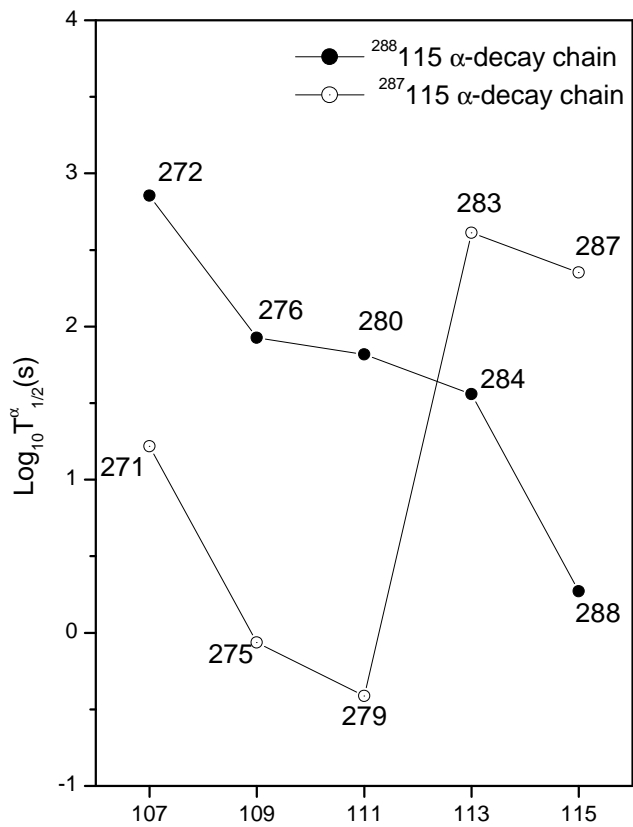
Fig. 6 The same as for Fig. 5 but for the preformation probability  $P_0$  and the penetration probability P.

Fig. 7 The same as for Fig. 5 but for the  $^{287}\text{115}$   $\alpha$ -decay chain.

Fig. 8 The same as for Fig. 6 but for  $^{287}\text{115}$   $\alpha$ -decay chain

Table 1: Comparison between experimental and calculated PCM  $\alpha$ -decay half-lives with other theoretical calculations. Calculated results are taken from Delta2 [11], NL3 parameter calculation [12], DDM3Y effective interaction[13], GLDM and VSS from [15].  $Q_{PCM}$  is calculated using binding energies from Audi-Wapstra[31] and Möller et al. nuclear data table[32].

$^AZ$	Q(Mev)		$\log_{10}T_{1/2}$ (sec)						
	Exp.	PCM	Exp.	PCM	DDM3Y	GLDM	VSS	Delta2	NL3
$^{288}_{115}$	10.61	10.99	-1.06	0.27	-0.39	-1.02	-0.0013	0.84	
$^{284}_{113}$	10.15	10.25	-0.32	1.56	0.187	-0.37	0.62	-0.95	
$^{280}_{111}$	9.87	9.98	0.56	1.82	0.28	-0.16	0.76	-0.93	
$^{276}_{109}$	9.85	9.80	-0.14	1.93	-0.35	-0.72	0.16	1.40	
$^{272}_{107}$	9.15	9.30	0.99	2.86	0.99		1.52	3.29	
$^{287}_{115}$	10.74	11.30	-1.45	2.35	-1.31	-1.33	-0.69	-1.09	-1.12
$^{283}_{113}$	10.26	10.60	-1.00	2.61	-0.69	-0.65	-0.03	-1.89	1.06
$^{279}_{111}$	10.52	10.45	-0.77	-0.41	-2.00	-1.92	-1.35	-0.85	-0.89
$^{275}_{109}$	10.48	10.12	-2.01	-0.06	-2.57	-2.39	-0.86	0.76	0.08
$^{271}_{107}$	-	9.50	-	1.22	0.65	-0.30	1.43	2.78	2.31



$Z \longrightarrow$

